LIFELINES: The Resilient Infrastructure Opportunity

WATER INFRASTRUCTURE RESILIENCE

Examples of Dams, Wastewater Treatment Plants, and Water Supply and Sanitation Systems

Clémentine Stip
Zhimin Mao
Laura Bonzanigo
Greg Browder
Jacob Tracy

WORLD BANK GROUP

1 2 3 4 19 18 17 16

Cover design by Brad Amburn.

Summary

Water systems are a special kind of infrastructure systems because they perform a dual role: they provide water services while also reducing risks to other services from natural hazards such as floods and droughts. This report aims to inform water system managers on the importance of and measures to build the resilience of water service provision to natural hazards and climate risks while ensuring that water systems can safeguard service provision by reducing their exposure to the risks associated with natural hazards. When choosing resilience measures, water systems managers should consider the following six principles while also incorporating the concept of decision making under deep uncertainty: 1) knowing the system through network analysis and criticality assessment; 2) improving maintenance to reduce vulnerability and improve resilience; 3) involving users for active demand management; 4) working with nature to manage and respond to risks; 5) developing and improving contingency management; and 6) applying innovation where appropriate. In addition, since water systems reduce the risks associated with certain natural hazards to other services like power, transport and water itself, such safeguard services should be accounted for when making the case for resilience investments in water systems.

Contents

List of Abbreviations

BMLWE	Beirut and Mount Lebanon Water Establishment
BOD	biochemical oxygen demand
CBS	container-based sanitation
COD	Chemical Oxygen Demand
CRCWSC	Cooperative Research Center for Water Sensitive Cities
CWS	Cutzamala Water System
DAWACO	Da Nang Water Supply Company
DMA	district metered area
DMDU	decision making under deep uncertainty
FEMA	Federal Emergency Management Agency
FMECS	failure mode, effects and criticality analysis
HCMC	Ho Chi Minh City
HDPE	high-density polyethylene
I&D	irrigation and drainage
ICOLD	International Commission on Large Dams
IHA	International Hydropower Association
LID	low-impact development
NRW	nonrevenue water
O&M	operations and maintenance
ONAS	National Sanitation Office of Senegal
PGA	peak ground acceleration
PVC	polyvinyl chloride
RCP	representative concentration pathway
RFID	radio frequency identification
SCADA	supervisory control and data acquisition
SNWA	Southern Nevada Water Authority
UVA	African Virtual University (Université Virtuelle Africaine)
WASA	Water & Sanitation Agency
WB	World Bank
WSS	water supply and sanitation
WWTP	wastewater treatment plant

All dollar amounts are U.S. dollars unless otherwise indicated.

1. Water Systems – Instrumental in Flood and Drought Management but Highly Vulnerable to Climate Change

Today, who hasn't heard of Cape Town's close call with "Day 0"? Or the strain put on Jordan's water resources by several waves of incoming refugees? Cities face all sorts of shocks and extreme events that challenge their ability to provide adequate levels of water supply and sanitation (WSS) services. With climate change affecting the variability and intensity of weather events, service providers are increasingly exposed to these shocks. In the case of Cape Town, relying predominantly on one source of water—rainfed reservoirs—locked the city in when rainfall patterns began to differ from historical levels. Without a clear demand management program in place, the service provider initially struggled to communicate the severity of the situation to consumers and had to resort to drastic measures to avoid a crisis.

Water systems can be defined as all the components that allow for the provision of water services from the source to the extraction, conveyance, storage, treatment, distribution, and consumption infrastructure, and combine both natural and man-built infrastructure elements. They consist of reservoirs, groundwater pumps, and transmission lines. They provide different services such as bulk water provision, standard water supply and sanitation services, and irrigation and drainage (I&D). This water infrastructure and its associated services to cities, industry, and farms are vulnerable to climate change. In addition to supplying water, however, water infrastructure is central to reducing natural hazard risks related to floods and droughts. Parts of the water system that contribute to risk reduction are, among others, multipurpose reservoirs, river embankments, stormwater drains, and coastal dikes. Figure 1 gives a graphical overview these services.

Figure 1. Water Systems and the services they provide

Water infrastructure has some special characteristics: (i) flood control infrastructure helps protect all types of networked infrastructure (power, transport, telecoms, and water); (ii) water services such as WSS and I&D experience unique climate risks, given that water is central to the service being provided; and (iii) water services are exposed to the same general risks as other network infrastructure when it comes to climate and natural hazards.

Resilience is understood as the ability of a system to continue functioning to a certain service level despite shocks. In evaluating the resilience of water systems, the dual role of water infrastructure must be accounted for and approached in an integrated manner. This paper discusses the resilience of water infrastructure and makes a case for the critical need to invest in resilience measures. It argues for the importance of building the resilience of water service provision to natural hazards and climate risks while ensuring that water systems can safeguard service provision by reducing their exposure to the risks associated with natural hazards. Current literature increasingly sees the latter role of water systems as an additional service (Caldecott 2018).

While it is easy to find examples of why planning for the resilience of water systems is critical, finding examples of service providers and planners that have successfully adapted to and prepared for climate change is more challenging.

On the one hand, water supply systems in many parts of the world will need to supply more water in a context of dwindling resources. Near Mexico City, climatic and demographic changes are increasingly challenging the ability of the Cutzamala Water System (CWS) to fulfill its operational mandate, especially as competition over water use grows. The CWS supplies about 30 percent of the Mexico City Metropolitan Area's water, through a complex interbasin transfer system. Rapid population growth and urban expansion are creating new water demands that are becoming more and more difficult to meet. Stress testing the CWS revealed high sensitivity of the current system to climate change—minor changes in precipitation and temperature could impair the system's ability to deliver the target supply at the historical reliability rate. By 2050, in almost all climate change projections, the system will be unable to reliably deliver enough water, without an increase in average precipitation. Given the high vulnerability of the system under current demand, it would certainly not be able to reliably meet higher demand, thus losing its critical role as a drought buffer.

Moreover, water resources are threatened in terms of their quality. In Kiribati, one of the world's smallest and most remote countries, the aquifer is threatened by seawater intrusion and overtopping as well as anthropogenic impacts. As the country consists of 33 coral islands—one raised and 32 low-lying— most of which are no more than two meters above mean sea level and only a few hundred meters wide, sea-level rise threatens both the country itself and its water resources. Families in urban areas tend to have pigs on their properties and the lack of black- and greywater management in the capital of South Tarawa leads to further contamination of the city's scarce groundwater resources. Rainwater, the second largest source of drinking water, is harvested from roofs and poorly stored, leading to point-of-use quality degradation. With lack of protection from large storm events, during which the waves and heavy rain erode the coast and destroy infrastructure, Kiribati is at the forefront of climate change vulnerability. In its Government Development Plan (2016–2019), Kiribati has identified improving access to quality climate change–resilient infrastructure in urban and rural areas as one of its key development commitments.

On the other hand, water-related natural disasters may also increase in severity and frequency. Nicaragua has been ranked fourth among the countries most affected by climate change and over the past years has experienced repeated flooding caused by more intense bursts of rain (Haynes 2017). In 2009, over 10,000 Nicaraguans were displaced from their homes because of rains linked to the La Niña phenomenon, while in 2011 a week-long storm put close to 10 percent of the country under water. A system of microdams has been installed throughout the city since the 1980s to reduce the sediment loads carried with floodwaters and thereby help alleviate the damages linked to urban flooding (Jha et al. 2011). Today, the city of Managua needs to look to measures that reduce runoff rather than simply convey it, if it is to build resilience to future events (IADB 2015). More specifically, low-impact development (LID) approaches that aim to store, infiltrate, evaporate, and detain runoff at the source—at the individual lot or neighborhood level—could help the city cope with intense rain events.

Water infrastructure is seldom built to withstand direct shocks, such as earthquakes and landslides, to the built assets. For instance, in March 2017, the water supply of Lima, the capital of Perú, was interrupted for four days by rains more intense than had ever been experienced, leading to severe landslides that filled the river with mud. The main water treatment plant could not handle the resulting turbidity and suspended solids. In general, management and planning are disconnected from the watershed and assume that future conditions will unfold within historical patterns, further undermining cities' resilience to shocks. Yet, service providers are already being challenged by events that lie outside the known historical records.

In addition to climate shocks, service providers have to contend with conflict and fragility. Jordan is one of the poorest countries in the world in terms of water availability. The 50-year mean annual rainfall in the country's capital, Amman, is about 350 millimeters, but with an average evaporation rate of about 90 percent, estimated water infiltration rates are just 4–10 percent of precipitation. While drought conditions are worsening, shifting the country to a new normal, its population has recently increased sharply. About 1.6 million refugees have entered the country, one-third of whom live in Amman. Despite local conservation and reuse efforts, the gap between supply and demand is increasing.

To build resilience, service providers must shift their approach to one that considers the robustness of the water system as a whole to different shocks under various possible futures. This approach involves looking at the basin scale to account for the elements of the water system that protect other services from natural hazards as well as the components of water service delivery. Flood control and management infrastructure can safeguard other services, like transportation and power systems. Multipurpose reservoirs, if operated well, can provide flood protection while generating power supply. In 2007, repeated rainstorms in New York City flooded several subway stations due to the lack of proper drainage infrastructure, impairing train service and endangering passengers. Studies in Seattle have shown that the use of green infrastructure to increase pervious surfaces in residential areas with no sewers or drains reduced runoff by 98 percent (City of Seattle 2007). Accounting for other services when designing components of the broader water system can help identify unplanned benefits and justify a project based on those contributions.

While a more resilient pipe can be built with more expensive materials than a less resilient pipe, a more resilient water system need not be more expensive than a less resilient water system.

As of today, few water service providers—be it for WSS, I&D, or flood management—have mechanisms in place to deal with such shocks and uncertainties. This paper aims to document specific instances where the resilience of water infrastructure was successfully built. Section 2 presents an analysis of the hazard exposure of dams and wastewater treatment plants, while sections 3 and 4 dive into the resilience of a specific kind of service providers: WSS utilities.

2. Partial Analysis of Hazard Exposure of Dams and Wastewater Treatment Plants

Water infrastructure is particularly vulnerable to natural hazards such as floods, earthquakes, landslides, and droughts at two levels. First, water infrastructure is exposed to unique climate risks compared to other types of infrastructure. Drought may reduce the ability of water supply and irrigation systems to deliver water, resulting in significant economic impacts (Damania et al. 2017). Similarly, climate risks associated with high precipitation may stress the design capacities of flood control infrastructure such as reservoirs, embankments, and drainage networks. Second, water infrastructure itself is subject to the same flood, earthquake, landslide, and storm hazards as power, road, and telecommunications infrastructure. For example, a flood may render a water plant inoperable, an earthquake may cause a dam to collapse, or a landslide may destroy a pipeline.

A global analysis of the exposure of all water infrastructure to natural hazards was not possible because of the lack of global data on water sector assets. Although some studies show promise in identifying vulnerable sections of water infrastructure (such as Bagriacik et al. 2016), they rely on high-quality data to describe the existing network, which limits their applicability to developing countries, where data may not be readily available. However, two assessments were undertaken to illustrate possible vulnerabilities: (i) a partial assessment of large dams, looking at their exposure to high river flows and earthquakes; and (ii) a case study of China's wastewater treatment plants (WWTPs) to understand the level of exposure faced by these critical water infrastructure elements to river floods and earthquakes (Hu et al. 2019).

Dams are critical for reducing downstream flooding but can also create disasters if they collapse because of high river inflows**.** The reservoirs created by dams can be used for multiple purposes, depending on the specific context. These potential uses include generating hydropower, providing water to cities or for irrigation, and reducing downstream flood risks. Dams are built with concrete spillways that release excess flows back into the river, downstream of the dam. The spillways are built with a specific design discharge to accommodate maximum flows, typically ranging from 500-year to 10,000-year or maximum probable discharges. If the discharge exceeds the spillway capacity, water flows over the dam itself, giving rise to an emergency. If the dam is made from earth and/or rock, the chance it will collapse is pretty high; on the other hand, if the dam is made of concrete, the chance of it collapsing is lower but an emergency situation could still arise.

Dam collapse may have catastrophic impacts on downstream communities. In Henan Province, China, the extreme rainfall produced by Typhoon Nina in 1975 went beyond the design criteria of the Banqiao Reservoir Dam. When exposed to such high levels of rainfall, the dam failed, killing tens of thousands of people, with estimates reaching up to 171,000.

Spillway design standards are usually based on the risk to downstream communities and on historical hydrological records. For example, a dam immediately upstream of a city typically meets higher standards than a dam in a rural area with low population density. However, over time, the population of downstream communities may grow or the risk tolerance of a country may change, making it necessary to increase the spillway capacity and take additional measures to ensure the structural integrity of the dam.

Until recently, climate change and its impacts on hydrological flows had not been considered in dam design. However, this practice is rapidly changing, the latest example being the Hydropower Sector

Climate Resilience Guide (2019) prepared under auspices of the International Hydropower Association (IHA), with technical and financial support from the World Bank (WB) and other international donors. The risks associated with underdesigning for future climates are multifold: dams may not be able to provide reliable services to users—be it water supply or power to cities, or irrigation water for agriculture—or help mitigate flood and drought risks. In fact, the dam itself could become a potential source of risk for downstream communities in the event of dam failure (Cervigni et al. 2015).

The exposure analysis presented here is based on the Global Reservoir and Dams Dataset (version 1.01), which contains 6,862 records of reservoirs and associated dams with a cumulative storage capacity of 6,179 cubic kilometers. These records only represent 20 percent of the dams registered by the International Commission on Large Dams (ICOLD), which lists more than 33,000 large dams. The Global Reservoir and Dams Dataset is thus limited and likely biased toward the developed world. However, as it is the only such georeferenced record of dams (Lehner et al. 2019), it was used for this exercise.

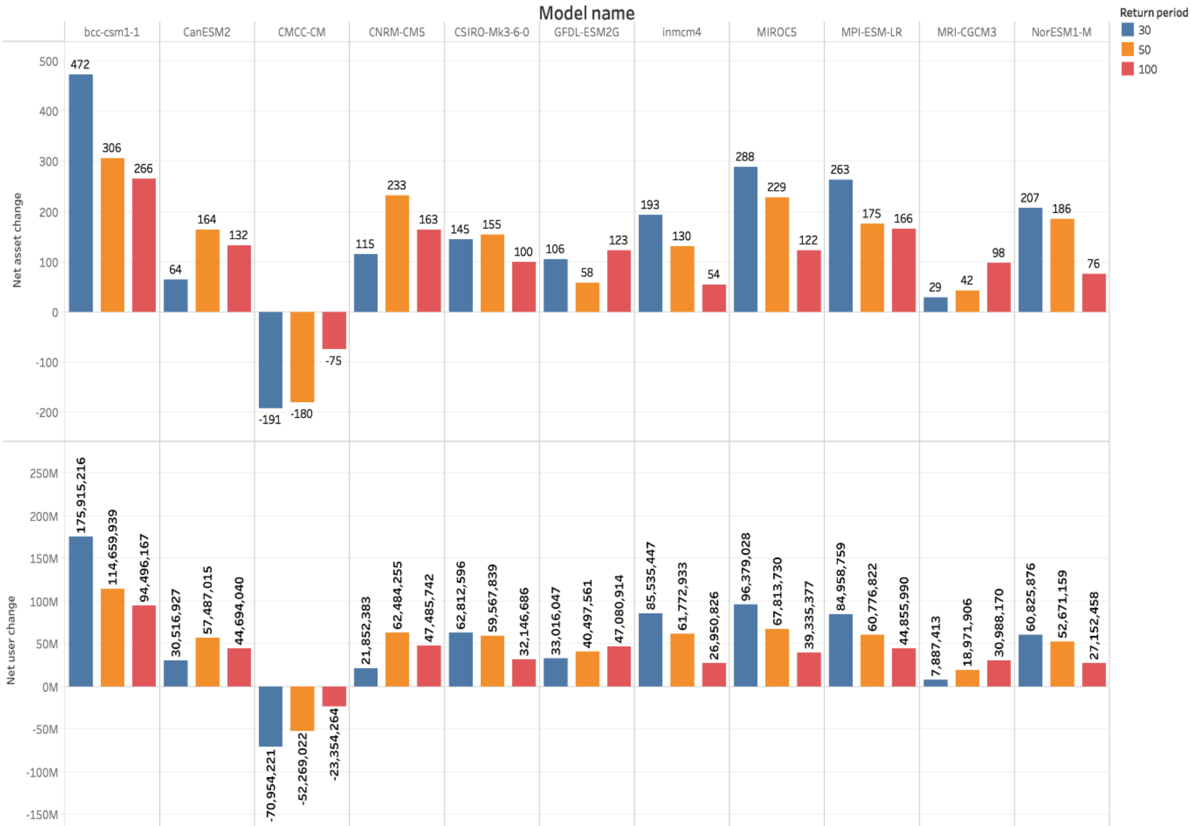
The level of exposure of dams to high river inflows—which could increase the chances of exceeding spillway capacity and possible dam collapse—is difficult to assess at the global level. In this exercise, the "river flood risk" information from the Think Hazard database (2019) was used as an indirect proxy for considering river flows into a reservoir. If a dam is in an area that is classified as having a "high river flood risk," this should indirectly and imprecisely correlate with high river flows. The Think Hazard database does not take climate change into account, but rather relies on historical data. Of the 6,862 dam sites in the Global Reservoir and Dams Dataset, 15 percent are in an area of high river flood risk, representing around 21 percent of the total global capacity. The actual risk of dam collapse depends on the design capacity of the spillway and the construction quality of the dam.

WWTPs often face flood hazards, as they are typically located in the lowest part of the network or water system. Wastewater collection systems usually work by gravity, to reduce energy costs, and treatment plants are generally located in low-lying, flood-prone areas adjacent to the rivers, deltas, or lakes that they discharge into. For wastewater systems with a combined sanitary and storm drainage network, heavy precipitation can overload system capacity, resulting in combined sewer overflows (CSO) of untreated sewage into the environment. Constructing CSO retention basins to temporarily store the water and later convey it back to the treatment plant is one option that some cities are pursuing, but this approach is very expensive and thus not affordable for all cities.

The case study on exposure of WWTPs to river floods and earthquakes is based on a dataset of 1,346 WWTPs in China, which includes plant locations and the population dependent on each plant. According to Hu et al. (2019), climate change will significantly increase the exposure of Chinese WWTPs to floods, even over the short term, with large potential impacts on users. The sign of this effect is consistent in 10 out of the 11 climate models considered, although the magnitude of the impacts varies across models. For an event with a 30-year return period under a scenario of moderate climate change, 35 percent of the WWTPs (472 out of 1346 plants) serving 176 million people could experience significant increases in flood risk by 2035.[1] Figure 2 shows the range of estimated impacts across different climate scenarios and time frames.

[1] For this analysis, a global river routing (CaMa-Flood) model is used that quantifies the change degree of flood exposures from the present time period (1980–2015) to the near-future time period (2016–35) to a far-future time period (2036–2055). These changes are evaluated for all floods exceeding 1 in 30, 1 in 50 and 1 in 100 events as estimated through an ensemble of 11 climate models under RCP4.5 and RCP8.5 climate scenarios. In this case, the exposure is defined as whether an asset is facing increasing flood hazard in the near- and far-future because of climate change.

Figure 2. Estimated Impacts across Different Climate Scenarios and Time Frames



Source: Hu et al. (2019)
Note: WWTP (top) and user exposure (bottom) to net change (positive, zero, or negative) of flood hazards for all models at return periods greater than 1 in 30 (blue bar), 1 in 50 (orange bar), and 1 in 100 years (red bar) for RCP 4.5. Time period: values indicate net change between (1986–2005) and (2006–2035).

Spatial variation is extremely important for planning climate-resilient infrastructure, as exposure of infrastructures to natural hazards is highly location-sensitive. For example, by 2035, under the MPI-ESM-LR model, flood hazards will be concentrated along the Yangtze River under the representative concentration pathway (RCP) 4.5 scenario. Under the RCP 8.5 scenario, the concentration of increasing flooding probability will happen in regions such as northern Heilongjiang and northern Inner Mongolia, unlike the case in RCP 4.5.

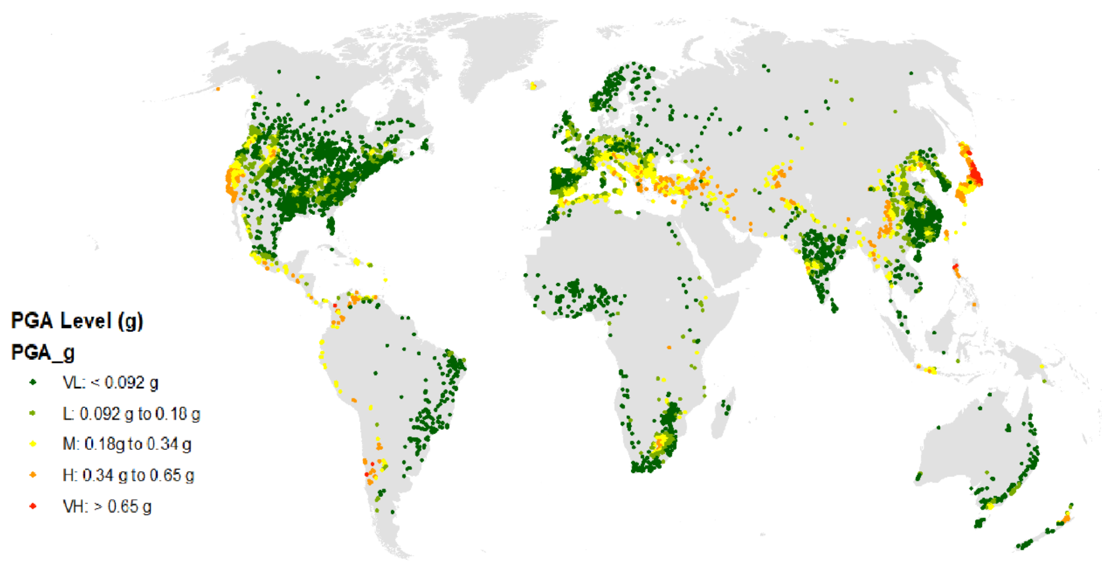
Earthquakes also pose significant hazards to water infrastructure components like dams and WWTPs. Earthquake hazards for dams are based on peak ground acceleration (PGA) for a 2,475-year event drawn from the UNISDR Global Assessment Report 2015 (Cardona et al. 2015). Normally, the return period for a maximum design earthquake (MDE)[2] is 10,000. However, since the global data set only has return periods of up to 2,475 years, this number was taken as the basis for assessment but should

[2] Maximum design earthquake (MDE), the maximum level of ground motion for which a structure is designed or evaluated. The associated performance requirement is that the project performs without loss of life or catastrophic failure (such as an uncontrolled release of a reservoir) although severe damage or economic loss may be tolerated.

still approximately indicate the earthquake hazard level. The higher the PGA, the greater the seismic risk. The Global Reservoir and Dams Dataset was used for this assessment.

As shown in figure 3, dams and reservoirs face the highest seismic hazard in Japan, central China, the U.S. West Coast, southern Europe, and the Middle East. About 2 percent of the dams considered in this study face very high PGA levels, that is, with a return period of 2,475 years. High-income countries have the largest number of dam sites exposed to earthquakes. However, upper-middle-income countries have the largest capacity of dams exposed to the risk of seismic shaking. This finding probably reflects the higher concentration of dams in richer economies and the large number of mega-dams in middle-income countries, particularly in China and Brazil.

Figure 3. PGA Faced by Dam Sites for a 2,475-Year Earthquake Event



Source: Own analysis.
Note: PGA = peak ground acceleration; H = high; L = low; M = medium; VH = very high; VL = very low.

Hu et al. (2019) find that, for China, earthquakes also pose a significant risk to wastewater treatment operations. In addition to PGA, the potential for soil liquefaction was considered.[3] For an earthquake with a return period of 250 years in China, 31 WWTPs are exposed to ground shaking of medium severity. Over half of these plants lie in areas with high liquefaction susceptibility, indicating their high vulnerability. Spatially, the western regions of mainland China and the surroundings of Beijing are prone to the highest seismic risks. Earthquake hazards are considered through data on PGA and soil liquefaction susceptibility for events of varying severities.

[3] In addition to peak ground acceleration, the analysis used liquefaction susceptibility as a proxy for potential damage across the return periods studied. Because state of practice, in situ testing for assessing liquefaction potential is not feasible at the global scale, the geospatial prediction models of Zhu, Baise, and Thompson (2017) were adopted. Liquefaction susceptibility is computed at a 1.2-kilometer grid resolution based on a global data set (Worden et al. 2017).

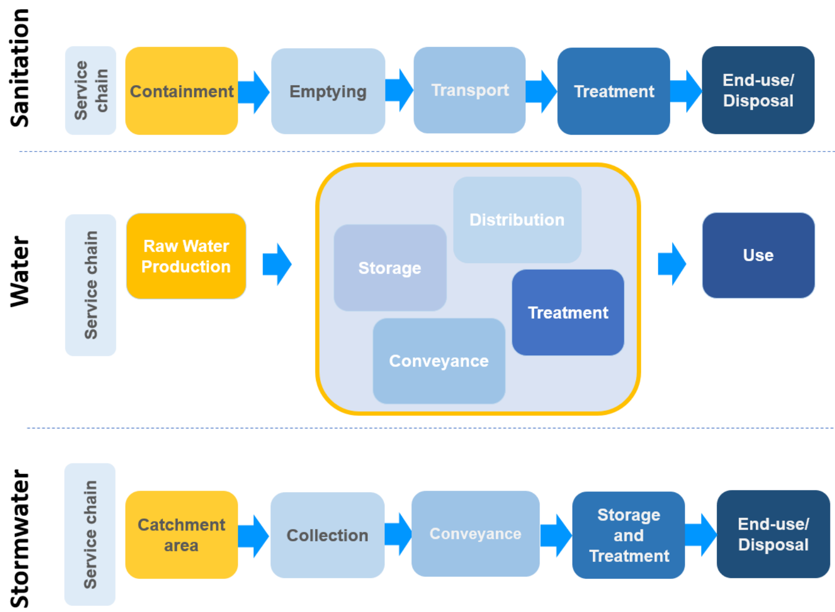
Water infrastructure resilience can be improved by using appropriate design standards, ensuring high-quality construction, operation, and maintenance, and taking climate impacts into account. This assessment only looks at hazards for dams and WWTPs. However, the actual risk associated with a given hazard depends on many factors. For example, China has comprehensive design standards to deal with seismic hazards, thus reducing risk. In turn, if dam spillways are properly designed, the risks associated with high river flows should be acceptable. Nevertheless, throughout the world, appropriate design standards are often not used, nor are operations and maintenance (O&M) conducted with a view to reducing risk. Yet climate change poses unique challenges: even if a dam or treatment plant was properly designed using historical information at the onset, future hydrological conditions may in fact be very different, requiring modifications in their design and/or operation.

The global exposure assessment to high river flows and earthquake exposures of dams and flood and earthquake exposure assessments of China's WWTPs demonstrate common risks faced by critical water infrastructures. First, while numbers are limited, some of the water infrastructures considered in these assessments do face high levels of flood and seismic risks. Failure to anticipate and prepare for the associated service disruptions and risks could lead to asset and economic losses. Second, many of the critical water infrastructure will face increased flood risks because of climate change. The uncertainties associated with frequency, severity, and location complicate decision making and preparedness. Third, one way to cope with uncertain and/or increased hazard risks is to consider updating the design standards. Considering the average age of the dam assets included in this study (over 50 years, that is, probably beyond their designed service life), proper maintenance, rehabilitation, and dam safety management could go a long way in reducing the probability of dam failure or service disruptions.

3. Building the Resilience of Water Service Provision: Focusing on Urban WSS Services

Given the critical role that urban WSS plays and will increasingly play for people's resilience, this section focuses on urban WSS utilities and service providers and their ability to provide services in a resilient manner. Urban spaces around the world are growing rapidly and expected to continue expanding significantly. By 2030, half of the world's population will be living in water-stressed, often urban areas. Global driving forces, including climate change, water scarcity, population growth, and urbanization, are expected to affect WSS services around the world (Damania et al. 2017). To hedge their bets against growing scarcity (linked to quantity and quality) and water-related risks, cities must develop resilient and varied portfolios of water resources. In addition, municipal water supply is only one of many water basin uses—urban service providers find themselves competing with other sectors for water within a basin, while potable water supply competes with other uses within the urban environment. Given the many stakeholders involved both at the city and basin level—sometimes even several basins —cities are seeking increasing control over water management and planning by maximizing local water sources, among others, through demand management and reuse.

Figure 4. Service Chains of the Urban Water Cycle



Source: Own elaboration.
Note: The water chain is not linear because the order of the steps can vary, depending on where in the chain the storage and treatment portion occur.

The urban "water system" is defined as the elements that make up the urban water cycle. They can be represented through the combination of the water service chain, sanitation service chain, and stormwater management chain (figure 4). This cycle is also affected by access to and quality of other urban services, such as solid waste management and housing. Elements of the urban water cycle need to be integrated with the city's urban development and with river basin management to maximize economic, social, and environmental benefits in an equitable manner and to build resilience.

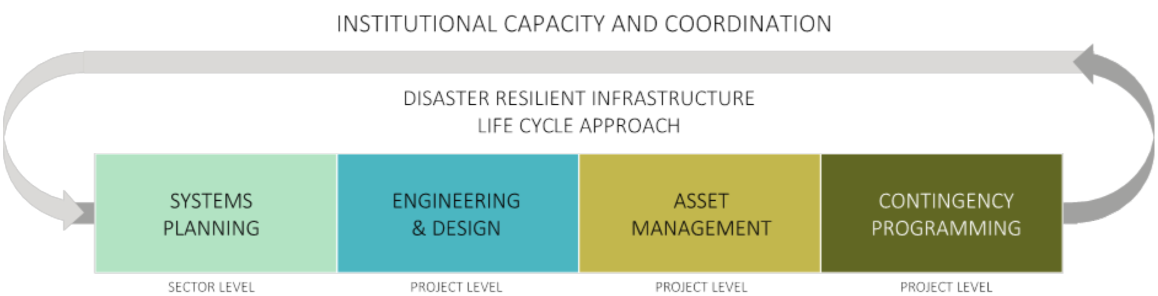
In the case of WSS services, resilience can be defined as the ability of the system to provide a reliable level of service despite external shocks, and to quickly rebound to the desired service levels after said shocks. Using this definition, the next section focuses on solutions and approaches that enhance service reliability broadly, though not all the examples discussed had resilience as their main objective.

4. Options for Increasing Resilience in Water

Whether the objective is to increase the resilience of service provision, as in the case of urban WSS, or to ensure that water infrastructure can continue contributing to the resilience of other infrastructure and services by managing floods or droughts, several methods and entry points may be considered. As mentioned above, resilience is defined as approaches that strengthen service reliability at any point of the service chain, which in turn improves the capacity of the system to continue providing an agreed level of service reliably, despite shocks, and respond to them. Often, the best way to build resilience is through a combination of infrastructure and institutional measures, supply augmentation and demand management, including measures to improve system efficiency.

Resilience happens at many levels. Adopting an integrated approach (figure 6) supports proper system design from the start and ensures capacity to respond to disasters throughout the system's life cycle. At the *system* level, centralizing information and enhancing stakeholder coordination builds institutional capacity, which in turns allows for integrated planning and service delivery. At the *sector* level, systems planning considers the vulnerability of areas where infrastructure is deployed, as well as the integration and redundancy of critical infrastructure to offer alternatives. At the *project* level, resilience can be built through proper engineering and design (for example, by carefully selecting materials and adapting design specifications), asset management (inventory, mapping, and vulnerability assessment of the infrastructure assets; prioritization of maintenance and repairs) and contingency programming (by developing the tools and protocols for emergency preparedness and response).

Figure 5. Integrated Approach to Life Cycle Costs Planning



Source: Internal World Bank document.

Involving stakeholders is equally important. Resilience can also be built at different stakeholder levels—through the service provider, the local government, basin stakeholders, and/or the end user. What is the right combination of measures and the appropriate level to target is highly context-specific and there is no silver bullet.

When exploring possible actions and measures, it is important to consider the uncertainties related to future conditions. Uncertainties related to water demand and supply because of climate change, and population growth and movement, as well as economic growth trajectories will affect system planning and asset management. The exposure assessment of dams and WWTPs, discussed in the previous section, underline the necessity to consider uncertainties related to natural hazards in terms of their intensity, frequency, and spatial distribution during engineering and design as well as contingency programming.

Planning for possible futures requires that decision makers account for deep uncertainties, such as highly uncertain changes in current stressors (population growth, water demand) and new types of failures brought about by climate change. Deep uncertainty is uncertainty that occurs when parties to a decision do not know or cannot agree on models relating to the key forces that shape the future, the probability distributions of key variables and parameters in these models, or the value of alternative outcomes. And yet, planning for the wrong future can lead to stranded assets, and severe consequences for water users.

The principles of decision making under deep uncertainty (DMDU) provide guidance on integrating such sources of uncertainty in the planning process. The most robust strategies perform well (though not necessarily optimally) according to several metrics of success under a wide number of future conditions—possibly including all stakeholders' views of what the future may look like—and thus build the broadest consensus. DMDU proposes accounting for different possible futures and testing the impacts of different variables on proposed actions and measures to see how their performance is affected. Planning for multiple scenarios avoids costly surprises and helps reach consensus. People can agree on a strategy or a project for different reasons. Exploring different futures enables possibly diverging future scenarios to be considered. This helps avoid gridlock and leads to a better understanding of how to prioritize beneficial actions across plausible futures.

Failure to adequately consider climate risks is likely to undermine the service provider's resilience and thus reduce the reliability and operational effectiveness in both the short and long term. This has a direct impact on the local economy, national resource security, and national economic growth. Water management planners and engineers have dealt with natural climate variances and disaster planning as part of the design process for many years. DMDU principles go further by proposing that different possible scenarios be considered in the planning process to ensure water systems are better equipped to deal with these possible futures were they to materialize.

This paper focuses on six principles that can help build the resilience of water systems and be implemented in complementary ways:

- Conducting network and criticality analysis to identify where to invest in strengthening or redundancy
- Improving maintenance, to reduce vulnerability
- Managing demand, to mitigate the impact of interruptions
- Working with nature and better integrating the WSS system with the management of the water sources
- Focusing on planning and institutions
- Testing new technologies and innovations such as decentralized sanitation, where available and sensible.

The remainder of this section introduces a methodology to incorporate these six principles into water systems resilience planning, followed by examples that illustrate their application.

4.1. Planning for Resilience without Predicting the Future

These principles all make sense on paper. However, how can water managers pick the most appropriate measures to enhance the resilience of their water system? To date, traditional planning methods have not considered the deep uncertainty surrounding many future conditions, which is further exacerbated by climate change.

To help utilities incorporate resilience and robustness in their choices, roadmaps recently published by the WB (World Bank 2018b; Ray and Brown 2015) build on different experiences in applying the six principles mentioned above and propose a 3-step process based on DMDU methodologies (www.deepuncertainty.org), which can inform the design of strategies necessary for robust and resilient service provision. Although the 2018 roadmap was specifically designed for WSS service provision in urban settings, the principles are applicable to broader resilient water systems planning.

Phase 1: Getting to know the system. The process starts with participatory work in which an extensive team (including planners, operators, and other stakeholders) identifies the problematic and critical elements of the system; the potential threats that may affect these elements, and the consequences of their individual or joint failure; the performance objectives the utility wants to achieve; and the available solutions. This scoping also identifies the tools, data, and models to be used in the subsequent phases.

Phase 2: Identifying vulnerabilities. Next, analysts (internal experts or external consultants) use the information gathered in Phase 1 to stress test the water system over a range of plausible futures and assess its performance under different conditions. This is done first for the system as is (status quo), and then for the different possible solutions and their combinations. Performance is measured against the objectives defined in phase 1. The stress test results in a concise description of the conditions most likely to cause the utility to fail to meet one or more objectives. These conditions are often summarized as scenarios that describe the combinations of factors that yield success or failure. Analysts also identify options that reduce vulnerability and improve the performance of both the entire system and critical elements over the same range of futures.

Phase 3: Choosing actions. Analysts organize these options into robust and flexible strategies and examine the trade-offs among them in meeting the agreed objectives under the scenarios identified in Phase 2. The options should include careful monitoring for conditions of concern (i.e., tracking whether the system is moving outside of the scenarios in which performance is acceptable).

As an integral part of all these steps, analysts present current vulnerabilities, options, and trade-offs to other teams in the water utility, the board, and possibly also to external stakeholders to define an acceptable, actionable, robust, and consensual road map. Depending on the complexity of the project, one or more rounds of participatory work with stakeholders will be required to refine the objectives or threats, or to adjust the options available to decision makers.

DMDU can thus help package the different possible options to secure the resilience of water systems without first having to predict future conditions. For instance, as part of the longer-term planning for Cape Town's water resilience, the city worked with Castalia Strategic Advisors to develop a sustainable water supply augmentation plan and stress test the different options under various climate and demand scenarios. Based on this assessment, the "insurance premium" for higher reliability was evaluated and inputs to adjust the water tariff were provided. Cape Town is now revising agreements with the National Water Department to ensure contingency measures for such drought scenarios will be put in place. Applying these methodologies in Lima, Peru, the water utility managed to save nearly 20 percent of its $2.4 billion investment plan by identifying which investments were unnecessary.

The following subsections will provide further guidance and examples on the implementation of the six principles mentioned above. Not all of the examples presented started out with the objective of building system resilience to climate change—plans were sometimes developed to deal with population growth, sometimes to address frequent electricity blackouts, sometimes merely for financial reasons (lower-costs options). However, ultimately, the measures taken as part of these plans invariably helped service providers increase the resilience of their assets and service provision, including flood and drought risk management.

4.2. Knowing the System: Network Analysis and Criticality

The first step to safeguarding service quality in the event of a shock is to know the system. Engineers usually know the sections of the system they manage well, but they rarely have an integrated view of the different pieces that fall under other management structures. For instance, and particularly in large water utilities, engineers in charge of the supply system rarely manage the distribution network as well. Yet, experience is increasingly showing that considering the whole network when evaluating options can lead to different (and in some cases, more cost-efficient) results than when looking at stand-alone investments and/or parts of a system. This also applies at the water system's scale, given that independent institutions are responsible for different components of the water system. For instance, a water utility may purchase water from a bulk water provider, who in turn depends on the dam owner or operator for some of that water supply. Discharge standards for water quality are set and enforced by the regulator, based on information from the water resources management agency but implemented by the service provider in charge of wastewater treatment (municipality, utility, sometimes industry itself). In this case, knowing the system in its entirety means (i) analyzing the different system components and their sensitivity to different risks in an integrated way and (ii) recognizing possible redundancies. Critical links and nodes should be identified, and appropriate solutions that secure service reliability developed. In turn, this will help prioritize actions to improve existing service provision and to maintain a specified level of service were these risks to materialize and one or more of these critical components to fail.

The typical methodology to assess criticality in a network is to carry out a failure mode, effects and criticality analysis (FMECA). This consists of mapping out all the components of the network and assessing under which conditions they would fail, what the effects of that failure would be, and what the impact of those effects would be on service delivery. Based on the latter, the "criticality" of each component can be ranked and a rating assigned accordingly. In the

Netherlands, breakdowns are ranked by level: a level 1 breakdown should never occur, as it would significantly disrupt service, a level 2 breakdown is allowed to occur every 3 years, and a level 3 breakdown is acceptable once a year because it is not vital to operations. Based on this categorization, a maintenance regime is determined that involves regularly checking the elements linked to level 1 breakdowns, but only storing spare parts for the elements in level 3, where a breakdown is expected more often. The level assigned to components also considers whether the asset is crucial to providing service to over 1,000 households or to a hospital, or for other services like firefighting. The WB supported the Da Nang Water Supply Company (DAWACO) in Vietnam in conducting such an asset analysis. DAWACO first developed its asset management system through a water operator partnership with VEI Dutch Water Operators, and the data from this system were subsequently used to carry out the analysis. A maintenance regime was then developed accordingly to enhance operational and resource allocation efficiency.

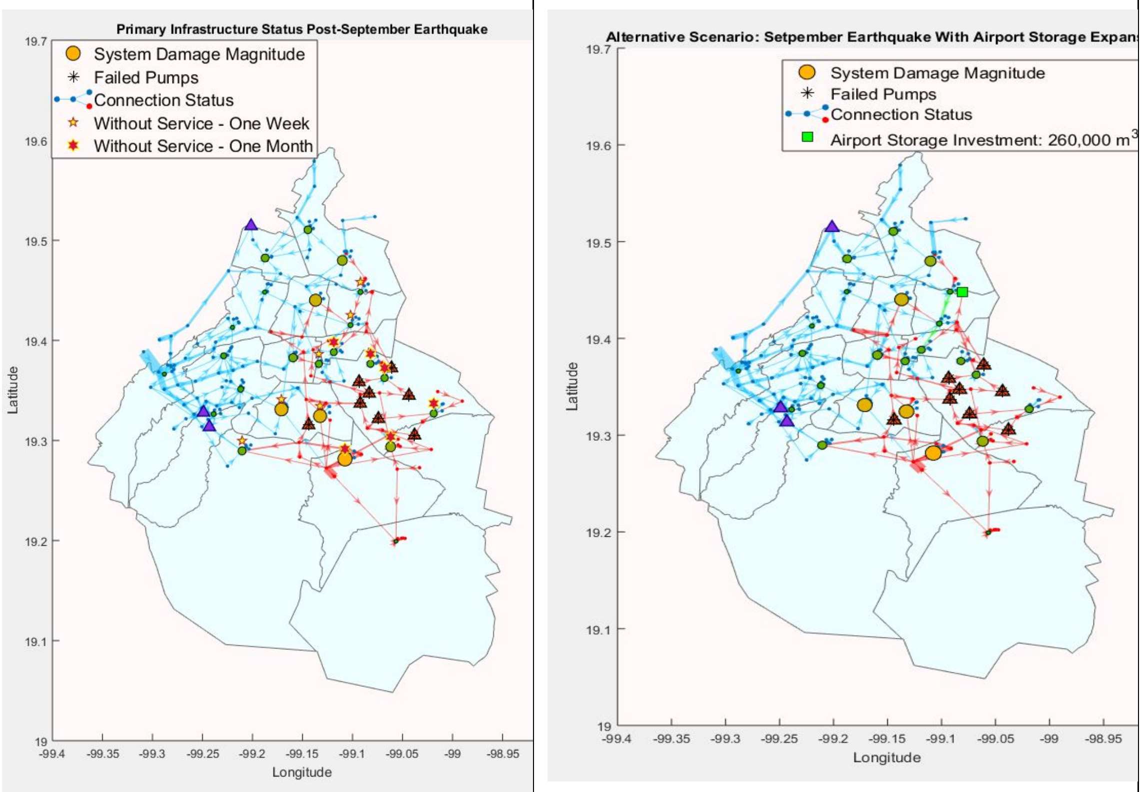
If a specific component is most sensitive to a specific failure mode, norms and standards can also be developed accordingly to safeguard this element. For instance, some industrial discharges are harmful for water bodies and associated ecosystems. If processed directly in the wastewater stream, they could also disrupt biological processes for wastewater treatment. Therefore, in some countries, the polluter bears the cost of the damage it does to the environment through its pollution. In the United States, the Environmental Protection Agency requires industry to pre-treat their wastewater before discharging it to the sewerage network, to avoid heavy metals, chemicals, and/or high concentrations of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) to enter the waste stream and disrupt the treatment process. Having such standards in place ensures accountability for remediation and avoids unplanned impacts on the treatment plant and water bodies.

Identifying critical elements of a water system also helps explore options for targeted redundancy (i.e., pinpointing where redundancy is most needed). Building redundancy in the water system—albeit not always possible—avoids service disruption if one component fails. Investing in redundancy could mean identifying alternative water supply options that are differently affected by specific risks (or affected by different risks). In Da Nang, Vietnam, differentiated sources enable the water supply service to continue when one of them fails. In Singapore, the Public Utilities Board (PUB) has defined four taps from which they can draw to meet water demand: imported water, wastewater reuse, stormwater, and desalination. Another way to diversify is illustrated by the Southern Nevada Water Authority's (SNWA) approach to water banking. Over time, the SNWA has "banked" the unused portion of its Colorado River allocation in aquifers across three states, saving 2,220 million cubic meters for use in times of shortage.

Redundancy can also mean building redundant infrastructure, for instance, within the network. In this case, water could come from the same source but reach end users through multiple channels. In the Netherlands and Japan, systems are designed as "loops" so that if one point in the network breaks down, other locations in the system can still be reached through an alternate route. In the Netherlands, this redundancy is also reflected in storage systems and water treatment plants. For example, river intakes can be shut down if the water quality in the river goes down, and after the intake the reservoir will have 5–6 months' worth of water supply stored, which is usually enough to "flush" the river from that pollution event. Water treatment plants themselves are built with storage capacity, which not only improves water quality at the inlet, through sunlight and retention, but also provides a water source for a given amount of time were the intake to be closed or the plant to malfunction.

In 2017, an earthquake left the Mexico City districts of Xochimilco, Tláhuac, and Iztacalco suffering from water shortages caused by severe damage to the water infrastructure. In Iztacalco, the most populous district, the 7.1 magnitude earthquake left more than 1.5 million residents without potable water supply. A network analysis mapped out Mexico City's extensive water distribution network and identified additional storage capacity at strategic locations (near the Airport on the east side of the city, for example) that could make several districts more resilient to future earthquakes of similar magnitude.

Figure 6. Network Analysis Comparing Earthquake Damage with and Without Additional Storage



a. Primary Infrastructure Status after September 2017 Earthquake	b. Primary Infrastructure status After September 2017 Earthquake with Airport Storage Expansion

Source: Own analysis.

Figure 7, panel a, shows primary infrastructure damage caused by the September 2017 earthquake. The damage to the aqueducts and pump stations in the southern and eastern systems left the corresponding sections of the city without service for a considerable length of time. Venustiano Carranza, Western Iztapalapa, Coyoacán, and Tlalpan were left without adequate service for a week; while Tlahuác, Iztapalapa (eastern, center, northern system), and Iztacalco were left without service for an entire month after the earthquake. Figure 7, panel b, shows how the service districts of Venustiano Carranza and Iztacalco could have increased their water system resilience if the city had invested in expanding the storage of the El Peñon tank near the airport. Given the minor secondary infrastructure damage in these areas (shown in the map), a tank with a storage capacity of 226,000 m^3, maintained at 75 percent of its storage capacity before the event, could have provided enough water to feed, by gravity, Venustiano Carranza's two districts and Iztacalco for three days in the wake of the earthquake, conservatively assuming 40 percent of the water would have been lost in transit and no effort would have been made to conserve water in the system.

Decentralized services can also be less vulnerable to disruptions in the main network, and thus more resilient to shocks affecting only one part of the network. For example, in Lima, having one WWTP to serve the whole city has put significant strain on the operator, SEDAPAL, as any issue with its functioning requires that untreated wastewater be released to the coast. In some places, for instance, Australia or Tucson (Arizona), water utilities have teamed up with city governments to provide rebates on household-level technologies like rainwater harvesting so that customers can fall back on a local water supply in case of drought or service disruption. Aguatuya, an NGO based in Bolivia, supports communities in developing and managing decentralized WSS systems in peri-urban areas of Cochabamba. These decentralized services have helped reach communities that were not benefitting from the city's centralized system. Moreover, they have also protected them from the service provision issues associated with the central city service provider, as communities manage their own services and can get technical support for specific repairs or O&M challenges that may arise. In addition, the decentralized WWTPs have made possible the reuse of treated effluent in local agriculture schemes, close to the point of use.

When looking at decentralized services, it is also important to consider the concept of social resilience. Very often, where formal services are not meeting users' needs for WSS—and infrastructure resilience is low, potentially leading to service disruptions—social resilience will be well-developed. Users may have access to several sources of water and use these for different purposes, depending on the water quality needed, as is the case in Kiribati, where nonpotable water needs are met with shallow wells, while potable water is preferably rainwater and cooking and washing are done with tap water. Such established social resilience measures need to be considered in project design. In some cases, the informal (or formal but "small") private sector will have filled service provision gaps and would be a key stakeholder to engage to avoid displacing livelihoods and established support networks. A recent firm-level survey conducted in Vietnam also indicated that firms that had purchased water equipment (such as tanks or pumps) in anticipation of water outages did not see their production costs go up when such service disruptions happen, compared to an increase of 8 percent otherwise (Russ & Hyland 2019). Therefore, a strategically stocked inventory of elements key to water supply access can support business continuity for relatively large water customers like firms.

Network analysis provides important decision-making inputs beyond the potable water supply network. To improve the knowledge and management of the aquifer it is responsible for, Orange County Water District developed a basin model through a process akin to network analysis. Its established network of wells and gauges provides it with real-time information about water flows in the Santa Ana River and at different points of the aquifer, which is fed into a model of the basin based on the United States Geological Survey (USGS) MODFLOW model (Woodside and Westropp 2015). The agency is therefore able to measure incoming stormwater flows and activate certain components of its aquifer recharge system, such as inflatable dams, depending on rain patterns and the corresponding quantity of water in the river, which flows towards the district's injection wells. Mapping out this system and having access to information at various important nodes allows the agency to optimize the recharge process, based on current river and weather conditions as well as the amount of water stored in the aquifer. In addition, it uses the model to predict possible future conditions in the aquifer, associated with certain climate scenarios, and prioritize projects and investments based on their impact on the aquifer.

A similar approach was taken in Jakarta, where network modeling of the flood management infrastructure component allowed improved decision making in response to urban floods. By modeling the different components of the urban flood management system and understanding how they (as nodes) are linked to waterways (rivers, canals, streams, etc.) in coastal mega-cities like Jakarta and how they interact during flood events, decision makers could prioritize the components most critical to flood preparation and to be activated during emergency conditions (Ogie et al. 2017). This model can also be used to evaluate the vulnerability of different flood management infrastructures and provide information on which actions can minimize the respective vulnerabilities, as well as to identify areas where additional infrastructure could increase a city's resilience to floods (Ogie et al. 2018).

Approaching the water system as a network and applying such network criticality analysis to its different components can therefore strengthen decision making in the event of a natural hazard, but also support planning for improved resilience.

4.3. Improving Maintenance to Reduce Vulnerability and Improve Resilience

Routine and periodic maintenance activities are essential to system resilience. Under normal conditions, regular maintenance activities not only ensure the system's adequate functioning, but also avoid the deterioration of system components during status quo operation. Maintenance thus extends the life of the system and can enhance its performance over time, as is the case for well-maintained biological wastewater treatment systems, among others.

The Federal Emergency Management Agency (FEMA) states that most cases of dam failure could have been avoided with proper O&M, which would also reduce the need for any major rehabilitation (FEMA 2018). Similarly, all flood management investments that contribute to climate adaptation, as identified by USAID and AECOM (2015), are unlikely to deliver the flood protection and adaptation benefits they are intended for if not adequately maintained.

In Salzburg, most water pipelines are over 100 years old but suffer very low water loss due to the city's effective strategic maintenance plan (European Union 2015). In Pula, Croatia, Pula Waterworks has had to adopt a seasonally adapted maintenance schedule because of the large influx of tourists in the summer, which more than doubles the population served. An essential element of the utility's maintenance routine is the reduction of leakages in spring, before the influx of summer visitors, focusing on those areas known to have leaks (because of the system's age or because of repeated recorded leakage). Pula is also one of the only water systems in the region with full control, through 100 percent district metering area (DMA) zones coverage, which enables them to closely monitor unplanned increases in flow year-round and detect leaks very quickly (European Union 2015).

Improving maintenance not only helps increase resilience to shocks, but also the financial sustainability of utilities. Proper system maintenance is often linked to lower levels of nonrevenue water (NRW). Improving the design of the distribution system, managing the pressure, detecting the leaks, and improving maintenance and metering lead to improved quality of service and help secure a positive financial flow that enables future investments in rehabilitation/maintenance, which in turn enhances resilience (Kingdom, Sy, and Soppe 2018).

Despite the obvious benefits of proper maintenance, utilities around the world struggle to pay for it. A WB study calculated that every year, over 32 billion cubic meters of treated water physically leak from urban water supply systems around the world, with half of these losses occurring in developing countries (Kingdom, Liemberger, and Marin 2006). In addition, when maintenance is irregular, the system is less likely to be inspected and well-known by the technicians, increasing the likelihood that illegal connections will go unnoticed, leading to commercial losses. The same study calculates these losses at 16 billion cubic meters per year globally. In developing countries, this represents an estimated loss of $5.8 billion per year, of which $2.6 billion corresponds to commercial losses— water that is treated and delivered to users but not billed. The latter amount represents a quarter of the total yearly investment in potable water infrastructure for the entire developing world and surpasses the WB's yearly aggregate lending to water projects for developing countries. If we consider that physical losses are most closely linked to lack of maintenance, and that it is "not unrealistic to expect that the high levels of physical losses could be reduced by half," NRW reductions of 8 billion cubic meters of treated water per year could be attained through improved leak detection, pipe replacement, and proper maintenance.

In Beirut, Lebanon, despite 90 percent water supply coverage, service continuity remains a challenge. In the summer, service can drop to 3 hours per day because of low water storage capacity, dry weather, high demand, and the poor condition of existing water networks. Technical and commercial water losses are estimated at around 40 percent. If no action is taken to improve distribution efficiency and increase storage capacity, chronic water shortages could affect Beirut as early as 2020. The service provider, the Beirut and Mount Lebanon Water Establishment (BMLWE), has implemented a performance-based contract for NRW reduction in a pilot area of its service area. The contract is ongoing and will be partially remunerated, based on the volume of NRW reduced.

Planning for resilience can help make a better case for financial support to maintenance. An analysis of the Cutzamala water system showed that proper maintenance is critical to long-term reliability and resilience. Without it, not even the most promising portfolio of infrastructure options identified through stress testing can ensure acceptable reliability. A sensitivity assessment of the system to lack of maintenance of major system components identified the elements whose failure/malfunctioning would have the most severe negative impacts on performance of the Cutzamala Water System in different scenarios. Though it is often easier to secure financing for larger capital investments than for daily and annual maintenance interventions, this finding demonstrates the importance of having a sound maintenance plan in place to realize the benefits of planned infrastructure—to have a system that is resilient to future shocks.

In Japan, the concept of strategic maintenance has also yielded significant savings in the O&M of the river structures the country uses for flood management (IWR 2011). These structures include embankments, flood gates, sluice ways, sluice pipes, drainage pump stations, and weirs, most of which were installed between 1960 and 1990. As a result, nearly 60 percent of these structures are more than 40 years old and need equipment renewal, entailing costs estimated in 2011 to be almost double the central government's annual budget. With strategic maintenance, in which maintenance is planned according to the actual, monitored state of the infrastructure and its mechanical components, and with a shift toward breakdown maintenance, in which repairs to noncritical equipment are postponed until the breakdown or damage of said elements, the estimated costs fell to just 30 percent above the existing budget.

In some cases, investing in NRW reduction would be a more efficient solution than developing new water sources. For the Bahamas, NRW reduction was a less costly alternative than new desalination plants (Laville 2015). Indeed, in New Providence, Bahamas, in 2012 over 90 percent of the water supply came from desalination while 58 percent was lost in the water system. The average price to consumers was $3.45 per cubic meter, about 10 times what the average person pays in the United States. As the development of 1 cubic meter of desalinated water was evaluated at $3 per cubic meter, a performance-based contract was developed to reduce NRW at $2 per cubic meter of water saved. In two years, NRW levels had been lowered from 58 to 32 percent, through a mix of pressure management, metering, leak detection, and network improvements.

Similarly, in Lima, a study applying the DMDU methodology showed that if the 2018 system improvements investments are maintained, which includes the completion of large investments to reduce NRW, the city will be robust to 27 percent of the future conditions explored—at no extra cost. In comparison, adding new drought-specific infrastructure for $129 million would only increase this robustness to 36 percent of future droughts (Groves et al. 2019). Therefore, the best option for Lima is to continue improving the existing systems, via NRW reduction, maintenance, and reoperation of the network—new large drought-specific investments would only be justified under extreme climate scenarios.

And again, knowing your system and its critical nodes can help save money. In Ho Chi Minh City (HCMC), Vietnam, the WB supported a performance-based contract targeting leakage detection and reduction, pipe replacements, and DMAs. The project was able to reduce NRW from 58 to 16 percent merely by replacing 6 percent of the connections. The associated water savings could serve 500,000 residents in HCMC, while the electricity saved could serve 2,500 households.

Maintenance allows the continued operation of water system components, ensuring their sustained ability to fulfill the functions they were designed for. Consequently, maintenance is a key component of a system's resilience in two respects: (i) it supports the reliability of the service provided by the system, and (ii) it ensures that the measures taken to ensure the resilience of the system in question have the desired results.

4.4. Demand Management and the Key Role of Users in Building Resilience

Demand management can help increase resilience in two ways. On the one hand, progressive demand management helps deal with stemming from water resources being increasingly scarce and variably available. Facing a drier climate coupled with population growth, the city of Zaragoza, Spain, has managed to reduce water consumption per capita by 30 percent since the early 2000s, to 99 liters per day—one of the lowest rates in the country and worldwide. This reduction has been achieved through a combination of water price adjustment, network rehabilitation, and public outreach and education (World Bank 2018) and reduced the city's need to invest in additional water sources.

On the other hand, demand management under contingency is a powerful measure to deal with disasters. The study in Lima mentioned earlier (Groves 2019) shows that by investing in the development of a comprehensive plan for demand management under contingency, costed at $3 million, the city will be able to manage 35 percent of future drought scenarios. Another example is how the city of Cape Town dealt with the three consecutive years of low rainfall in 2014–16: Day 0 was avoided due to the success of the demand management measures implemented, which reduced use by 400 million liters per day (MLD)—40 percent of normal use—between 2015 and 2018.

A focus on demand management also recognizes the central role of customers in building resilience in their water system. In Belén, Costa Rica, focus groups with customers of the water utility helped identify different low-cost demand reduction measures to be tested in a study (World Bank and ideas42 2015). These discussions showed customers generally agreed on the importance of conserving water but didn't necessarily think they themselves should reduce use and knew little about what a high or low water consumption might be. The study results demonstrated that a descriptive social norm measure based on neighborhood comparison (through stickers on water bills) was most effective among high-consumption users and more effective than citywide comparisons. Among low-consumption users, a plan-making intervention—providing customers with information to devise their own water use reduction plan, specifying targets, measures, and milestones—was most effective. Including users in program design through both focus groups and field testing yielded important findings for the Belen service provider to incorporate into future programming.

Active customer participation in demand management can provide some flexibility in responding to a drought event. When Governor Brown mandated that California utilities reduce consumption by 25 percent across the state during the recent drought, some cities reached that target by capitalizing on existing demand management measures through "business as almost usual." The Irvine Ranch Water District water billing system uses customized water budgets, calculated based on landscape square footage of each property, number of residents, and daily weather or evapotranspiration, among others. The commodity charge is then calculated using an increasing block tariff to dissuade customers from using more than their allocated water budget. This structure has increased drought-proofing in Irvine, allowing the district to weather the record droughts of 2009 and 2014 without having to declare a shortage or impose overt mandatory restrictions. In fact, customers already being very sensitized to the importance of water conservation made additional measures more effective.

Involving the public early on can also help avoid future failures through increased accountability. A resilience- focused study of the Oroville dam failure in California in February 2017 showed that, though maintenance failure and engineering shortcomings were officially identified as the culprits, sound decision making and attention to civil society could have averted the almost-crisis (Hollins et al. 2018). Indeed, the problematic suite of decisions that led to the failure could be traced back to issues in the dam's governance that had been pointed out in several public comment sessions. Taking a resilience approach, the authors retrace the decision-making processes that culminated in the dam's overflow and almost-failure to show that it resulted from factors previously flagged by the public. These factors had formed the basis for poor engineering and maintenance decisions instead of being used to prevent the failure.

Involving users in decision making ensures transparency and ownership in the resilience-building process. Users of a service also play an important role in managing the demand side of that service. In the same way that water consumption has been successfully reduced in several places, thus reducing the need for costlier infrastructure-based supply augmentation schemes, users can provide inputs on the way services can be adapted to better serve them and the environment.

4.5. Working with Nature and Integrated Water Management

Water engineers traditionally tend to think that grey infrastructure can ensure service provision, including flood and drought management. However, the existing infrastructure sometimes no longer suffices—and building new grey infrastructure can be expensive in terms of capital and O&M costs. Therefore, in recent years, water managers around the world have begun exploring how to integrate green infrastructure with existing grey infrastructure to increase the resilience of their systems. Combining green and grey infrastructure can entail lower costs, higher benefits, and more sustainable infrastructure solutions (Browder et al., 2019).

Today, integrated green and grey infrastructure solutions are often used for stormwater and flood management, but also to help city and other water users manage droughts.

To manage floods and the associated fecal contamination from the overflow of septic tanks and latrines, the RISE Program is working in communities exposed to tidal flooding and equipped with poor sanitation solutions in Suva, Fiji. Each flooding event causes fecal contamination to spread, as the flood water carries the waste from the latrines into streets and public spaces. The proposed interventions would mix simplified sewerage with wetlands, to contain the waste, use walkways to separate the community from the flood water and filter it as it flows in and out of the area. In Teresina, Brazil, leisure spaces with elevated spaces for community gathering were created in flood-prone, low-income areas to facilitate the infiltration of flood flows. The China Sponge City Program aims to reduce the impacts of flooding through a mix of low-impact development measures, urban greenery, and drainage infrastructure—realizing what the Australian Cooperative Research Center for Water Sensitive Cities (CRCWSC) calls its vision of the "city as a water catchment." CRCWSC's ambitious goal is for 80 percent of urban areas to reuse 70 percent of rainwater by 2020, which would help ensure the resilience of these cities to floods. Cities in the United States are also increasingly seeing green infrastructure as a key component of stormwater management in the future. In San Francisco, managing stormwater upstream of the drains is actually one of the city's priorities. By keeping more stormwater out of the sewers, the city will be better positioned to respond to storm surges.

In Namibia, severe drought led Windhoek to be one of the first cities in the world to introduce full-scale wastewater reclamation (or direct potable reuse) in 1968. The wastewater is treated to potable level and directly injected into the aquifer the city derives its water supply from, and it now provides 25 percent of Windhoek's water. In Orange County, California, the aquifer is also used as a buffer for dry conditions. Stormwater infiltration is promoted through canals and inflatable dams, while highly treated wastewater is injected into the aquifer to recharge it. This managed aquifer recharge increases the drinking water supply available to Orange County service providers, while also serving as a barrier to seawater intrusion and supporting flood management in the now highly developed area.

In Kiribati, a WB study is evaluating the potential for greywater infiltration through gravel and sand filtration to safely dispose of the water locally in South Tarawa, while also improving water quality. This approach would be easily integrated with the local practice of discharging greywater to the porous sand-based ground and may actually enhance that practice through the use of a contained discharge area and more effective filtration media. Given the additional treatment, it is believed that this infiltration would slowly improve the quality of the water in the top layer of the aquifer, where inhabitants currently draw water from for non-potable uses. While no conclusions can be drawn at this time because of the lack of information on water quality in the aquifer's different layers, the proposed greywater infiltration seems to resonate with local inhabitants.

While measures integrating green and grey infrastructure have not necessarily been tested in a DMDU setting, unlike measures based on grey infrastructure only, their demonstrated reductions in the impacts of both floods and droughts—as well as other natural hazards—make them a key component of building future resilience for water systems worldwide.

4.6. Contingency Planning and Management

The measures discussed above help water systems manage shocks and secure a reliable service supply to their users. However, it is nearly impossible for a utility to protect itself against all risks. Therefore, planning for the residual risk allows utilities to successfully manage it and use available resources more effectively.

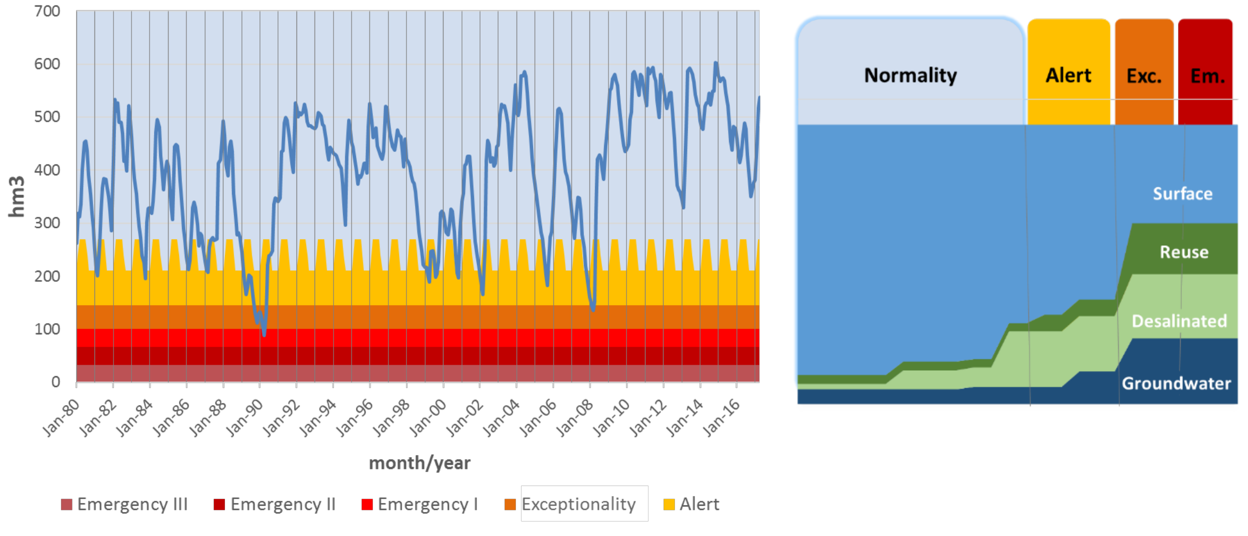
First, it is crucial to know the nature and magnitude of the residual risk. Where only one infrastructure is involved, the design standard indicates the levels of failure. In the case of a more complex system, DMDU methodologies provide the answer: they help concisely describe the set of conditions a system is vulnerable to. For instance, the frequency of rainfall and its intensity in the two previous years could be influential factors in a system's ability to deliver water to its users, making the system vulnerable were they to drop below a certain threshold. The DMDU process specifically helps identify such factors.

Once water managers know the limits of their system, emergency planning can begin. Contingency plans set out the measures to be taken by a service provider were an emergency or unforeseen incident to occur.

Categorizing water resources according to their vulnerability to certain risks and establishing whether they need further development can improve the water resources planning process. In the United States, the SNWA categorizes its water sources according to their availability and development strategy: *permanent* resources, available for use over a 50-year planning horizon; *temporary* resources, which can be used to meet potential short-term gaps between supply and demand; and *future* resources, which will be developed during the 50-year planning horizon. Though the SNWA has to date not exceeded its Colorado River allocation, its water resources planning already embeds several fallback scenarios should the drought significantly reduce water availability (World Bank 2018a).

Contingency plans also help ensure that the local stakeholders know how to continue providing a certain level of WSS service were the normal service provision to be interrupted. For instance, in Spain, Aigües de Barcelona's *Drought Management Plan* tracks key water system performance indicators and helps the water utility respond through agreed measures to guarantee the drinking water supply and mitigate the economic impacts (World Bank 2018a). Based on surface storage levels, the utility has defined drought thresholds that define what sources to draw from (figure 8). In the case of a water shortage, the more expensive sources (reuse and desalination) would be used first, and the strategic buffer sources (the aquifer) next. As a last resort, the city would tap into water normally reserved for environmental flows to meet Barcelona's water needs.[4]

Figure 7. Barcelona's Drought Management Plan



Source: PowerPoint presentation "Water Management in Barcelona Metropolitan Area," delivered by Ramón Creus in 2017.
Note: hm3 = cubic hectometer; exc. = exceptional situation; em. = emergency. The left pane shows historical surface storage levels and drought threshold values (1980–2016), while the right pane shows the mix of water sources by threshold category.

[4] The Drought Management Plan is graphically explained in detail in a PowerPoint presentation titled "Water Management in Barcelona Metropolitan Area," delivered in 2017 by Ramón Creus.

It is important to plan for contingency management in the short term within broader planning efforts for the longer term, as the decision on which priority actions to take could be different in this case than when planning for the two horizons separately. When looking to navigate many possible futures, planners must contemplate whether actions are irreversible and whether they can be connected across time. Many low-regret short-term actions (e.g., conservation incentives, self-insurance, pricing, and maintenance) are reversible and easily paired with challenging capital-intensive projects. In some cases, the latter can be eliminated because of the successful implementation of the former. Flexibility is crucial to avoid overinvestments and stranded assets, and it helps more efficiently allocate the available budget across the priorities of the service provider.

For instance, aligned coordination on water supply and sanitation, but also on other elements of the water cycle like stormwater management, can help identify and develop drought-proof water sources, or manage drainage in ways less disruptive to the urban space. In Orange County, joint planning between the OCWD (in charge of bulk water supply) and OCSD (in charge of sanitation) helped identify wastewater reuse as a key cost saver for both the sanitation district—thanks to avoided seawater outfall costs—and to the water district, by securing a new drought-proof source of water. OCWD also manages stormwater and has played an important role in the recharge of the aquifer using that source. In general, a utility managing water supply and sanitation together may reduce the transaction costs associated with coordination while being better placed to identify opportunities to close the water cycle.

In some cases, service providers will have to manage service interruptions linked to infrastructure failure. Better management of such interruptions can make it possible for users to accept more frequent interruptions and lower overall cost. In Pakistan, Faisalabad Water & Sanitation Agency (WASA) evaluated the coping cost for people who were not receiving water services from the utility to justify a tariff increase. Indeed, households were spending about PKR 2,272 (~15 USD) on water per month, of which 86 percent was spent on electricity to extract well water and on bottled water for drinking. Such measures, focusing on users' adaptive capacity, can be built in from the design and planning stages to prepare for risks that cannot be eliminated. This would be the case if a utility, as part of its contingency plan, had a standing contract with water tankers to provide water were the system to fail in an emergency situation. In HCMC, Vietnam, the climate adaptation plan proposes "increasing end users' resilience" as an efficient adaptation measure, ensuring that the utility has alternative water sources readily available for at least one day of interruptions. In Tucson, Arizona, the utility encouraged customers to invest in household-level rainwater harvesting infrastructure through rebates to ensure they would have localized water sources in the event of a drought. Though not always financed by the service provider, household tanks are a common way for users to cope with shortages and intermittent supply. Ultimately, it may be less expensive to make users able to cope with interruptions than to try and prevent all service interruptions.

Alternative service arrangements can also be put in place to minimize system failure and prioritize service delivery. Often, integrating sectors and working with the "small" private sector provides utilities with a new way to reach unserved areas, sometimes faster and more inclusively than through conventional approaches—like covering the whole city with sewerage infrastructure. In Maputo, a pilot project trained solid waste management operators to include fecal sludge collection on their solid waste collection routes. This process improved efficiency by building on the routes these collectors were already doing, while also reducing their idle capacity as it gave them the option to switch between services. In the Philippines, after a typhoon, water tankers were contracted to ensure service continuity despite infrastructure damage. Although such alternative service arrangements may not be motivated by resilience when they are first implemented, they can still build the reliability of the service if well-regulated because they integrate existing service arrangements (private sector already providing the service can start being supervised by the utility for quality assurance, for example) and provide extra capacity were conventional or centralized services to fail.

Contingency planning serves the double role of ensuring there are measures in place to deal with residual risks while familiarizing people with the possible failure scenarios and associated responses. In alignment with DMDU principles, planners should consider short-term and long-term measures and their interactions, and account for the diversity of stakeholders involved in and affected by those decisions.

4.7. Innovation

Given the pace at which technology is changing, many opportunities exist for technical and process-based innovation to improve service provision and thereby strengthen resilience. This section explores how innovation can affect the resilience of an asset, support the reallocation of resources toward resilience, and provide decentralized services less vulnerable to centralized shocks.

The resilience of an asset can be improved by using more resistant materials or technologies that require less maintenance. In the case of a pipe system, water service providers increasingly favor high-density polyethylene (HDPE) and polyvinyl chloride (PVC) pipes (plastics) because of their versatility and ease of transport and installation. The lifespan of these plastic pipes is, however, shorter than that of their more durable and less flexible counterparts: 50–70 years and 50–100 years respectively, compared to several hundred years for reinforced concrete (Sustainable Solutions Corporation 2017). Similarly, vitrified clay pipes are still found to be functional in centuries-old installations but are no longer used today, given their inability to withstand high pressures and the limitations on pipe length in their manufacturing process (mixing clay and shale). In the case of pipes, the savings associated with manufacturing and adaptability outweigh the durability of the material.

This approach is particularly useful in view of recent technological advances in pipe maintenance technology. Trenchless leak detection has become increasingly popular, as water utilities seek to reduce NRW and target repairs in the areas leaking most water so as to allocate resources most efficiently. These approaches typically use robots or sensors to detect changes in water pressure through sound waves, or visually inspect the pipe from inside. In Washington, D.C., the Echologics ePulse pipe condition assessment was used to assess pipe replacement needs in the water network. While the original plan was to replace 100 km of pipes, ePulse's assessment revealed that 32 km of pipe were still in good condition. Thus, the assessment allowed DC Water to better target leaks, redirecting $14 million of investment as a result (Georges et al. 2018). Similarly, Curapipe Ltd uses a proprietary sealant to plug leaks and cracks directly in the pipe, as their PIG train (name of the technology) passes through.

Such approaches can also be used for sewer networks. Innovations in this space include smaller, more nimble robots that can inspect the pipes without disturbing traffic and causing health hazards (manholes open for a long time) and can still provide a full view of the pipe, while being small enough to reach where traditional CCTV technology cannot. In England, Thames Water applied an acoustic pipeline inspection tool called SewerBatt™, reducing CCTV surveys by 33 percent and cutting associated costs by $1.5 million per year (Georges et al. 2018).

Digitalization is also helping optimize maintenance at different water system scales for utilities. In Barcelona, a central dashboard depicts the city's canals and river system, including dikes and flow controllers. Aigües de Barcelona employees can control any portion of the system from a distance, opening and closing valves as needed to control the flow. Similarly, if there is any change in the flow regime, they are notified automatically and can remediate it in time. Optimization is also possible at smaller scales, for example, focusing on specific steps of the water treatment process. The company Sand-Cycle has developed small radio frequency identification (RFID) tags—the same technology used to "tag" animals, made of bioglass and as small as sand grains—to monitor the performance of sand filters, one of the most widely used water treatment technologies. These tags are placed within the sand filter bed and monitor the movement of the water in real-time, providing direct information about filter health to operators (Georges et al. 2018)

Accurate data and remote sensing have increased service providers' responsiveness and ability to know their system, and hence plan for its resilience. In Las Vegas, the level of Lake Mead serves as a trigger for different water management measures, and reservoir levels are also used in Barcelona to identify the right water supply mix, based on temporal or seasonal scarcity of the resource. Being able to access such numbers in real time has enabled quicker, more reactive decision making and the refining of associated decision making. In remote areas of Panama and Colombia, remote sensors have been tested to monitor water flow, water tank levels, and water quality in real time, uploading the information to the cloud so that the municipal government is aware of an issue as soon as it arises and can take action. Similarly, in the United States, many water utilities have rolled out smart meters that significantly reduce meter-reading costs and allow users' consumption levels to be read at any time of the day, influencing water price strategies to encourage off-peak use.

Increased access to data and technology can also help strengthen planning and operation processes to better target resources and improve business continuity. Supervisory control and data acquisition (SCADA), a system that is widely used by utilities across the globe to monitor operation regimes, can now be managed through a mobile application, alerting staff through just-in-time work orders and increasing the proactivity of O&M. Big data have also made possible analyses of flow patterns and leakage detection to predict material needs and pipe replacements in advance, thereby optimizing operation, avoiding wasted resources, and enhancing business continuity. A recent study carried out in Dhaka, Bangladesh, used earth observation data to map out access to basic services in slum areas, based on elements identifiable from space such as roof material, and the presence of garbage and runoff in the streets. Based on these insights and correlating them with survey data from the Dhaka WASH Poverty Diagnostics, the study made recommendations regarding the areas where WSS services were lagging and where the city government could focus future investments.

Reduction in the cost of providing services can also free up resources to be reinvested toward resilience. Resource recovery technologies and approaches have played an important role in decentralizing service provision and generating a new source of funds while helping to reduce the footprint of wastewater and its associated products. In Sandvika, Norway, heat exchangers are placed in the town's main sewer and combined with a heat pump to extract waste heat from the wastewater, filling over 50 percent of the offices' and residential energy needs (Georges et al. 2018). Several cities around the world have witnessed the construction of self-sufficient buildings, where waste and wastewater are collected and treated on-site, generating energy and treated water for nonpotable uses. In Kiribati, the WB is looking at supporting the rollout of household-level greywater filters to support families in disposing of their greywater in a safe way while recharging the locally polluted groundwater lenses in South Tarawa. This approach would help slowly improve the quality of the groundwater in the top layer while ensuring inhabitants are not exposed to any running greywater. In addition, this approach builds on existing practices and the already existing social resilience in the island's urban area. Recovery of water, energy, and nutrients from wastewater, as well as increasingly efficient wastewater treatment systems, are all contributing to these advancements.

Thinking innovatively does not always mean developing a new, cutting-edge technology. Sometimes, a process innovation can be more impactful and resilient. A good example is the development of container-based sanitation (CBS) services, which focus on a whole-service chain approach to reach unserved areas that are difficult to access and unlikely to be reached by conventional infrastructure solutions in the short term. They are particularly adequate for slums, informal areas, or areas with many tenants, as they provide a solution that does not require building infrastructure. Customers rent a toilet that is portable and consists of a lined container, a seat, and some cover material, and pay a monthly fee to receive a pickup service from the service providers. For example, in the case of Sanivation in Naivasha, Kenya, the collectors use tuk-tuks to easily access customers' homes, despite the narrow unpaved streets. The innovative approach of CBS provides more flexibility to align with the customers' schedules and payment possibilities (weekly, or customized payment plans), can be part of an adaptive sanitation planning process and avoids technology "lock-in," while helping customers get used to paying for a sanitation service.

In addition, CBS services can be more resilient to climate variations, particularly floods and droughts, than other solutions. In Haiti, CBS service users highlighted that they could continue using their toilets during floods, unlike traditional latrines. In Nairobi, some service users saw the fact that Fresh Life Toilets are waterless as a distinct advantage in a water-scarce environment without piped water and, consequently, water for household use is costly and needs to be hauled over considerable distances (World Bank 2019).

The University of Virginia has supported the development of call centers for fecal sludge management in several cities in Africa, looking to bridge and regulate the private sector while not excluding it from the service provision space. In Dakar, Senegal, for example, the African Virtual University (UVA) has worked with the National Sanitation Office of Senegal (ONAS) to establish a network of truck drivers who were already collecting and transporting fecal sludge on a private basis and to centralize demands through a call center. Then, using a mobile-based bidding system, drivers can bid on the demands and get assigned routes, based on distance and the price they offer. The bid assignment is worked out through software and operated by ONAS staff. These types of process innovation can improve the efficiency of service provision and help decentralize the responsibility for service provision, so that one company or private operator unable to provide a service does not disrupt the whole chain.

Innovation should enhance resilience, not hinder it. In some cases, very sophisticated innovative technology may be difficult to fix when it fails, if there is no capacity installed to manage it. In this case, resilience would mean that the capacity to return to the previous state should be spread widely. At the Dutch water company Vitens Evidens, staff perform an annual drill where everything has to be done by hand to ensure employees do not rely too much on electronics and automatized systems and could still perform their main functions were those systems to fail. In the Philippines, solar panels were installed so that pumping stations in key points of the networks could continue to operate and maintain a minimal capacity to pump water if the electricity grid were to break down. In Mandalay, Myanmar, the poor operation of a chlorine disinfection system resulted in seven deaths after the operators injected too much chlorine gas into the water. Had the staff been properly trained or the system been simpler, this issue would have been easily avoided. From that moment, the operator abandoned chlorine and began serving untreated water, nullifying any benefits from the costly construction of this water treatment system. Though the technology itself is not particularly “innovative,” this story does emphasize the importance of capacity building of the operator to streamline new technologies into water service operation. More broadly, though fostering innovative thinking and approaches holds great potential to improve service reliability and even resilience, supporting capacity building and institutional change are key to ensuring we move beyond pilot scales and ensure ownership and integration into day-to-day processes.

5. Conclusions

Water systems are a special kind of infrastructure systems because they perform a dual role. First and foremost, they are critical in providing water services and, therefore, the resilience of the system to natural hazards and climate risks is intrinsically linked to the provision of water as the end product.

Though the paper deep dives into the provision of WSS services, the principles presented apply to the other water services as well. Thus, the main elements that the paper presents aim to inform water management planners as they consider measures to increase the resilience of the services that water infrastructure both provides and safeguards. In deciding on these measures, the main elements to keep in mind are the following:

- Service providers need to be willing to engage in long-term planning that accounts for the deep uncertainties they face and will continue to affect service provision in the future. Though climate change and natural hazard risks affect the ability of service providers to provide the service levels they aspire to, it can also provide opportunities for utilities to readjust priorities and reduce costs in the long term. Applying DMDU principles by understanding the system, agreeing with stakeholders on priorities, and considering potential actions in light of possible futures can help service providers improve their systems' resilience without having to predict the future.
- Approaching the water system as a network and applying network criticality analysis to its different components is an integral part of getting to know the system and identifying redundancy. Network criticality analysis can strengthen decision making in the event of a natural hazard by pre-identifying the components most likely to fail, the measures to reinforce them, and the actions to take if such failure arises, but also support planning for improved resilience by helping prioritize actions and areas for intervention.
- A sound maintenance regime is essential to the sustained functioning of any infrastructure system, no matter its complexity. Maintenance contributes to system resilience by supporting the reliability of the service provided, while ensuring that the measures put in place for the resilience of this infrastructure have the intended results.
- As with all planning processes, stakeholder involvement is key to successfully building the resilience of water systems. Involving users in decision making ensures transparency and ownership in the resilience- building process, while the users of a service play an important role in managing the demand side of that service and can give input on the way services should be adapted to better serve them and the environment.
- Integrating green and grey infrastructure along the whole water management and water service provision cycle has demonstrated reductions in the impacts from natural hazards. Planners should consider this integration in building future resilience for water systems, specifically in interactions with other sectors and when looking for lower-cost, higher-benefit options.
- Since service providers cannot protect themselves against all risks, planning for the residual risk allows them to successfully manage it and use available resources more

effectively. Contingency planning serves the double role of ensuring there are measures in place to deal with residual risks while familiarizing people the possible failure scenarios and associated responses.

Innovation has brought several enhancements to resilience planning through, among others, more resilient materials, improved management, and freeing up of resources from typical capital or O&M costs to invest in resilience. While future innovation is likely to continue contributing to these aspects and should be invested in and supported, planners should avoid lock-ins by ensuing that innovative solutions remain flexible and are accompanied by appropriate capacity building.

Moreover, water systems provide an important additional service. They reduce the risks associated with certain natural hazards to other services like power, transport and water itself by limiting their exposure to floods and droughts, thereby protecting the water, power, and transport networks. Though estimating this risk and quantifying the contribution of water systems to the resilience of other infrastructure systems is beyond the scope of this paper, water systems resilience provide an essential additional benefit of great importance when considering broader infrastructure resilience. Beyond protection water service provision, ensuring the resilience of water systems is therefore also critical to safeguarding other systems themselves and should be accounted for when making the case for resilience investments in water systems.

References

Browder, Greg; Ozment, Suzanne; Rehberger Bescos, Irene; Gartner, Todd; Lange, Glenn-Marie. 2019. Integrating Green and Gray: Creating Next Generation Infrastructure. Washington, DC: World Bank and World Resources Institute. World Bank and World Resources Institute. https://openknowledge.worldbank.org/handle/10986/31430 License: CC BY 4.0.

Caldecott, Ben. 2018. *Water Infrastructure for Climate Adaptation – The opportunity to scale up funding and financing.* World Water Council.

Carlsbad Desalination Project. 2017. "How it works." https://www.carlsbaddesal.com/how-it-works.html. Accessed April 6, 2019.

Cervigni, Raffaello, Rikard Liden, James E. Neumann, and Kenneth M. Strzepek. 2015. *Enhancing the Climate Resilience of Africa's Infrastructure: The Power and Water Sectors.* Overview booklet. World Bank, Washington, DC. License: Creative Commons Attribution CC BY 3.0 IGO.

City of Seattle. 2007. "Seattle's Natural Drainage Systems;" The City of Seattle, Seattle Public Utilities.

CRCWSC (Cooperative Research Center for Water Sensitive Cities). 2016. "Urban Heat, Heat Reduction and Public Health." https://watersensitivecities.org.au/wp-content/uploads/2016/08/Urban-Heat-Briefing_Final.pdf.

CRED and EM-DAT 2019. *The OFDA/CRED - International Disaster Database.* Available at: www.emdat.be (accessed March 11, 2019).

CRED and UNISDR. 2018. *Economic Losses, Poverty & Disasters 1998–2017*. Available at: https://www.unisdr.org/files/61119_credeconomiclosses.pdf.

Damania, Richard; Desbureaux, Sébastien; Hyland, Marie; Islam, Asif; Moore, Scott; Rodella, Aude-Sophie; Russ, Jason; and Esha Zaveri. 2017. Uncharted Waters : The New Economics of Water Scarcity and Variability. Washington, DC: World Bank.

European Union. 2015. *EU Reference document Good Practices on Leakage Management WFD CIS WG PoM.* Case Study document.

FEMA. 2018. "Dam Operation and Maintenance." Accessible at https://www.fema.gov/dam-operation-and-maintenance. Last Updated: June 16, 2018.

Furmage, Benjamin. 2019. "A Water Sensitive Approach to More Resilient Cities." Presentation at South-South Knowledge Exchange workshop on Integrated Urban Water Management. Jakarta, January 2019.

Gammon, Katharine. 2012. "Extracting Nutrients from Raw Sewage, To Grow Our Plants Extra Big." Fast Company. Published March 27, 2012. https://www.fastcompany.com/1679532/extracting-nutrients-from-raw-sewage-to-grow-our-plants-extra-big. Accessed April 6, 2019.

Georges, Karyn; Hall, Bethany; McNally, Thomas; and Ben Tam. 2018. "The Smart Water Utility. 21st Century Water Utilities." Isle Utilities.

Heymans, Chris; Eberhard, Rolfe; Ehrhardt, David; and Shannon Riley. 2016. *Providing Water to Poor People in African Cities Effectively: Lessons from Utility Reforms.* Water and Sanitation Program Report. Washington, DC: World Bank.

Hollins, Lucien X., Eisenberg, Daniel A., and Thomas P. Seager. 2018. "Risk and Resilience at the Oroville Dam." *Infrastructures* 3. 49. 10.3390.

Hu, X., Pant, R., Zorn, C., Lim, W., Koks, E., and Mao, Z. 2019. "Methodology and Findings for the Exposure Analysis of the Chinese Wastewater Sector to Flooding and Earthquakes Hazards." Background paper prepared for this report.

Jha, Abhas; Lamond, Jessica; Bloch, Robin; Bhattacharya, Namrata; Lopez, Ana; Papachristodoulou, Nikolaos; Bird, Alan; Proverbs, David; Davies, John; and Robert Barker. 2011. *Five Feet High and Rising: Cities and Flooding in the 21st Century (English)*. Policy Research working paper no. WPS 5648. Washington, DC: World Bank.

Kalra, Nidhi Rajiv; Groves, David G.; Bonzanigo, Laura; Molina Pérez, Edmundo; Ramos, Cayo; Brandon, Carter J.; and Iván Rodríguez Cabanillas. 2015. "Robust Decision-Making in the Water Sector: A Strategy for Implementing Lima's Long-Term Water Resources Master Plan (English)." Policy Research working paper no. WPS 7439. Washington, D.C.: World Bank Group.

Kingdom, Bill, Jemima Sy, and Gerhardus Soppe. 2018. *The Use of Performance-Based Contracts for Nonrevenue Water Reduction: Output of the Global Program on Developing Good PBC Practices for Managing NRW.* Washington, DC: World Bank.

Laville, Glen. 2015. "Reduction of Non-Revenue Water Performance Based Contract." New Providence, The Bahamas. Presentation at World Bank and Interamerican Development Bank Workshop, December 2015.

Lehner, Bernhard & Reidy Liermann, Catherine & Revenga, Carmen & Vörösmarty, Charles & Fekete, Balazs & Crouzet, Philippe & Doell, Petra & Endejan, Marcel & Frenken, Karen & Magome, Jun & Nilsson, Christer & Robertson, James & Rödel, Raimund & Sindorf, Nikolai & Wisser, Dominik. 2019. Global Reservoir and Dam (GRanD) database.

Mumbengegwi, D., Li, T. and Muhoza, J. P. 2018. "An Overview of Sewage Treatment Rates in Chinese Cities." *International Journal of Waste Resources* 8 (2): 333. doi: 10.4172/2252-5211.1000333.

NYC Department of Environmental Protection. 2006. *City Water Tunnel No. 3 Fact Sheet.* Report archived from the original (PDF) on January 1, 2013. Retrieved October 21, 2013.

Ogie, R.I., Holderness, T., Dunbar, M., and Turpin, E. 2017. "Spatio-Topological Network Analysis of Hydrological Infrastructure as a Decision Support Tool for Flood Mitigation in Coastal Mega-Cities." *Environment and Planning B: Urban Analytics and City Science* 44 (4): 718–739.

Ogie, R.I., Holderness, T., Dunn, S., and Turpin, E. 2018. "Assessing the Vulnerability of Hydrological Infrastructure to Flood Damage in Coastal Cities of Developing Nations." *Computers, Environment and Urban Systems* 68: 97–109.

Ray, Patrick A.; Brown, Casey M. 2015. *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework.* Washington, DC: World Bank.

Sand-Cycle. Monitoring of Continuous Sand Filters. https://sand-cycle.com/. Accessed April 6, 2019.

Sustainable Solutions Corporation. 2017. "Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials." Institute for Environmental Research and Education and NSF Sustainability. April 2017. Accessed at https://www.uni-bell.org/files/Reports/Life_Cycle_Assessment_of_PVC_Water_and_Sewer_Pipe_and_Comparative_Sustainability_Analysis_of_Pipe_Materials.pdf.

Tierney, K.J. 2002. "Business Impacts of the Northridge Earthquake." *Journal of Contingencies and Crisis Management* 5: 87–97.

USAID and AECOM. 2015. *A Methodology for Incorporating Climate Change Adaptation in Infrastructure Planning and Design – Sanitation.* Report on Global Climate Change, Adaptation, and Infrastructure Issues Knowledge Management Support. November 2015.

U.S. Army Engineer Institute for Water Resources (IWR). 2011. *Flood Risk Management Approaches: As Being Practiced in Japan, Netherlands, United Kingdom and United States.* IWR Report. No. 2011-R-08. September 2011. Accessed at <https://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/2011-R-08.pdf>

Ward, P. J., Jongman, B., Sperna Weiland, F., Bouwman, A. A., van Beek, R., Bierkens, M.F.P., Ligtvoet, W., and Winsemius H. C. 2013. "Assessing Flood Risk at the Global Scale: Model Setup, Results, and Sensitivity." *Environmental Research Letters* 8 (4): http://dx.doi.org/10.1088/1748-9326/8/4/044019

Woodside, G., and M. Westropp. 2015. "Orange County Water District Groundwater Management Plan, 2015 Update." Orange County Water District (OCWD). June 15, 2015.

Worden, C.B., D.J., W., and E.M., T. 2017. Development of an Open-Source Hybrid Global Vs30 Model, Seismological Society of America Annual Meeting, April 21–23, Pasadena, CA.

World Bank. 2018a. *Water Scarce Cities: Thriving in a Finite World – Full Report.* Washington, DC: World Bank. http://documents.worldbank.org/curated/en/281071523547385102/pdf/125187-REVISED-WP-W17100.pdf.

———. 2018b. *Building the Resilience of WSS Utilities to Climate Change and Other Threats: A Road Map.* Washington, DC: World Bank.

———. 2019. *Evaluating the Potential of Container-Based Sanitation.* Washington, DC: World Bank.

———. Forthcoming. *City-Wide Inclusive Water Supplies.* Washington, DC: World Bank.

World Bank and ideas42. 2015. "A Behavioral Approach to Water Conservation: Evidence from a Randomized Evaluation in Costa Rica."

Zhang, Q.H., Yang, W.N., Ngo, H.H., Guo, W.S., Jin, P.K., Dzakpasu, M., Yang, S.J., Wang, Q., Wang, X.C., and D. Ao. 2016. "Current Status of Urban Wastewater Treatment Plants in China." *Environment International* 92–93: 11–22. doi: 10.1016/j.envint.2016.03.024.

Zhu, J., Baise, L.G., and E.M. Thompson. 2017. "An Updated Geospatial Liquefaction Model for Global Application." *Bulletin of the Seismological Society of America* 107: 1365–1385.